THE ASTROPHYSICAL JOURNAL, 307:694–697, 1986 August 15

A MODEL ATMOSPHERE ANALYSIS OF THE FAINT EARLY-TYPE HALO STAR PHL 346

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Received 1985 December 26; accepted 1986 February 5

ABSTRACT

Stellar equivalent widths and hydrogen line profiles, measured from high-resolution optical spectra obtained with the 2.5 m Isaac Newton Telescope, are used in conjunction with model atmosphere calculations to determine the atmospheric parameters and chemical composition of the faint, high galactic latitude early-type star PHL 346. The effective temperature ($T_{\rm eff} = 22{,}600 \pm 1000$ K) and surface gravity ($\log g = 3.6 \pm 0.2$), as well as the chemical composition, are found to be similar to those of normal OB stars. Therefore, it is concluded that PHL 346 is an ordinary Population I object, at a z distance of 8.7 ± 1.5 kpc. The relatively small stellar velocity in the z-direction ($V_z \approx +56 \pm 10$ km s^{-1}) then implies that PHL 346 must have been formed in the halo, possibly from galactic fountain material at a z distance of ~ 6 kpc.

Subject headings: stars: atmospheres — stars: early-type — stars: individual

I. INTRODUCTION

The nature and origin of high-latitude early-type stars have been a subject of discussion over the past few years. Several authors believe them to be subluminous, nearby objects whose spectra mimic those of normal stars at classification dispersions (see Carrasco, Aguilar, and Recillas-Cruz 1982, and references therein), similar to the UV-bright stars in globular clusters (de Boer 1985). However, subluminous stars can be differentiated from normal OB stars using accurate quantitative spectral analyses, since the former usually have Population II chemical compositions (Tobin and Kaufmann 1984).

Recent work has revealed that many relatively bright ($V \leq 10$) early-type halo stars are indeed normal objects, at distances of typically 2 kpc from the plane (Tobin and Kilkenny 1981; Keenan, Dufton, and McKeith 1982; Keenan and Dufton 1983, 1984). They must either have been formed in the halo (Keenan and Lennon 1984) or, alternatively, accelerated out of the disk (Keenan and Dufton 1983; Tobin 1986) via close binary disruption (Stone 1979) or cluster ejection (Gies and Bolton 1986).

In this paper we extend this earlier work to a fainter ($V \approx 11.5$), high-latitude ($b \approx -58°$), early-type star PHL 346. Kilkenny, Hill, and Brown (1977) assigned a spectral classification of B1, which would imply that PHL 346 is ~ 5 kpc from the galactic plane if main-sequence, and further if it is a giant or supergiant. It is important to determine the extent of these faint objects, especially since their sight lines may be of great use as tracers of distant halo interstellar gas (see, e.g., Keenan *et al.* 1983; Harris and Bromage 1984).

II. OBSERVATIONS

Observational data were obtained for PHL 346 with the 2.5 m Isaac Newton Telescope on La Palma, Canary Islands, in 1985 August. The IDS spectrograph was used with camera B and the Joyce-Yoon 2400 grooves mm^{-1} grating, with an IPCS as the detector, yielding ~ 8 Å mm^{-1} spectra in the blue visible region with a resolution (full width half-maximum) of ~ 0.3 Å. Three wavelength regions were observed: 3900–4150 Å, 4150–4380 Å, and 4420–4660 Å.

The observing procedures and data reduction methods were similar to those previously used for spectra obtained with the 3.9 m Anglo-Australian Telescope in which further details can be found (see Keenan *et al.* 1984; Keenan, Brown, and Lennon 1986). In Figure 1 the spectrum of PHL 346 is shown from 3990 to 4040 Å to illustrate the quality of the present observational data.

Equivalent widths of helium and metal lines in the spectra of PHL 346 were measured using the DIPSO reduction package (Giddings and Settle 1980) by fitting Gaussian profiles to the observational data. Details of the procedures involved may be found in Brown *et al.* (1986). In Table 1 the equivalent widths are summarized, a realistic error estimate being approximately $\pm 10\%$ for the strong lines and ± 20 mÅ for the weaker ones.

III. METHOD OF ANALYSIS

The method of analysis has been described in detail by Keenan, Brown, and Lennon (1986) and Brown *et al.* (1986). Briefly, it consisted of comparing measured stellar Strömgren colors, hydrogen line profiles, and helium and metal line equivalent widths with those predicted by local thermodynamic equilibrium (LTE) model atmosphere calculations. The derivation of atmospheric parameters and abundances are discussed separately below.

a) Atmospheric Parameters

An effective temperature for PHL 346 was deduced initially from the reddening free Strömgren color index $[c_1]$ $(= c_1 - 0.2[b - y])$, using the $[c_1] - T_{\rm eff}$ calibration of Relyea and Kurucz (1978). The observed index, $[c_1] = 0.108$ (Kilkenny *et al.* 1977), lead to an effective temperature $T_{\rm eff} = 22{,}600$ K. This should be accurate to ± 1000 K on the Kurucz (1979) fully line-blanketed grid of models on which it is derived. Subsequent analysis of the Si II/Si III/Si IV and C II/C III relative line strengths (see § III*b*) confirmed this temperature.

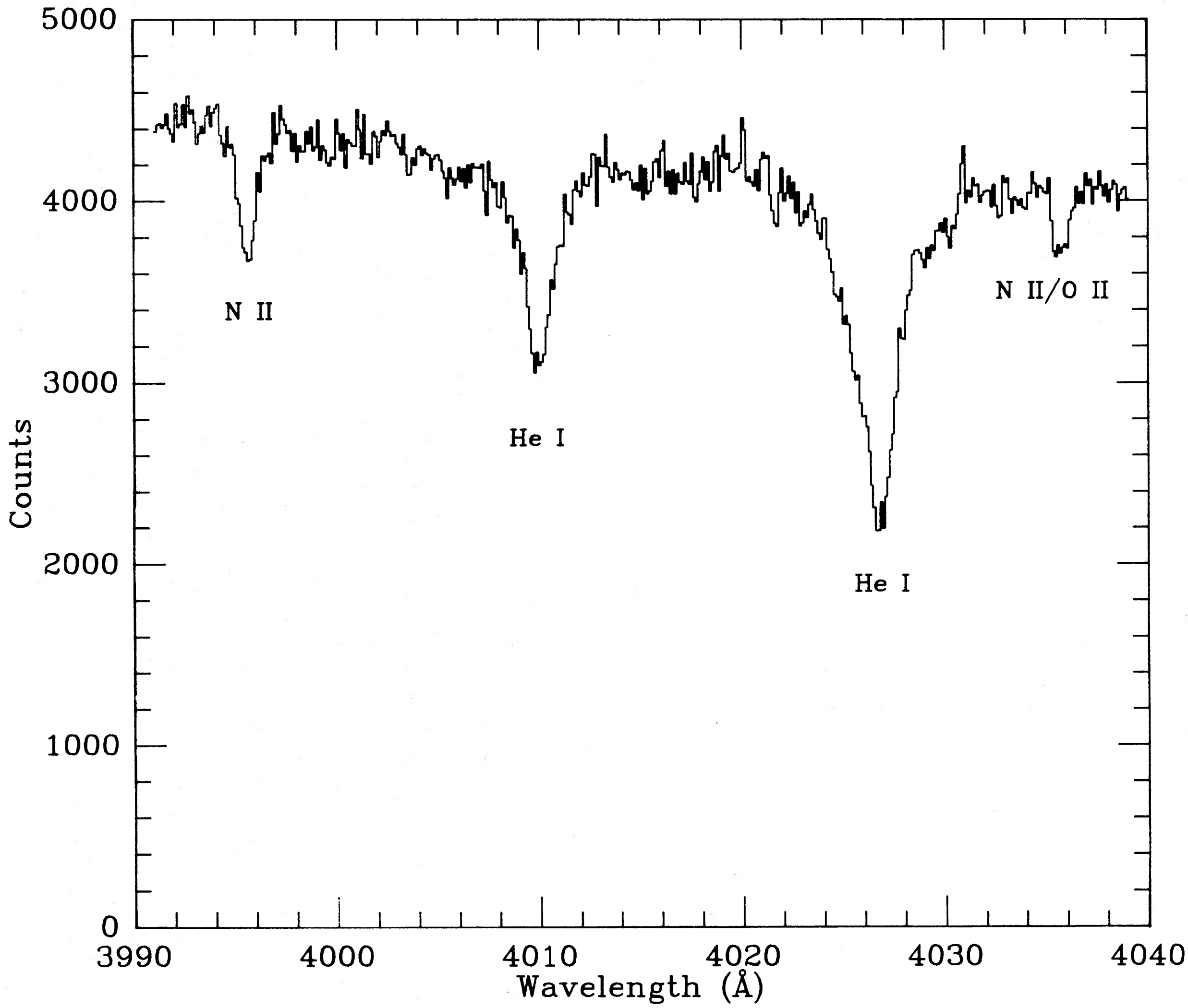

FIG. 1.—Portion of an unsmoothed INT spectrum of PHL 346. Stellar absorption lines of N II, He I, and N II/O II are clearly visible in the spectrum at 3995, 4009, 4026, and 4035 Å. The N II/O II feature has an equivalent width of 76 mÅ.

A surface gravity was determined by fitting theoretical Hγ and Hδ line profiles to the observations. The hydrogen line broadening theory of Vidal, Cooper, and Smith (1970, 1973) was used in the calculations. Model atmospheres were generated with the ATLAS6 code, and are very similar to the published models (Kurucz 1979). A logarithmic gravity, log g, of 3.6 was compatible with both of the hydrogen lines, observational uncertainties in the line profiles leading to an error estimate of approximately ± 0.2 dex.

The microturbulent velocity (V_t) appropriate to an LTE analysis of PHL 346 was determined by constructing a curve of growth for the O II lines observed in the spectra, the method being similar to that used by Kane, McKeith, and Dufton (1981) and Keenan and Lennon (1984). A value of $V_t = 12 \pm 3$ km s^{-1} was deduced, which, given the results of Dufton, Durrant, and Durrant (1981), may be a slight overestimate. However, it is in good agreement with those found in previous LTE analyses of giant and supergiant stars (see Keenan and Lennon 1984, and references therein).

b) Abundances

Using the atmospheric parameters discussed above, helium and metal abundances were deduced by comparing observed line strengths with those predicted from LTE model atmospheres generated with the ATLAS6 code (see Brown *et al.* 1986 for more details). Although non–LTE calculations are available for several of the species considered in the present analysis (e.g., He I, Dufton and McKeith 1980; C II, Lennon 1983; N II, Dufton and Hibbert 1981; Si II, Si III, Si IV, Lennon *et al.* 1986), they were not used since, in general, they changed the derived abundances by less than 0.2 dex.

IV. RESULTS AND DISCUSSION

The mean logarithmic helium and metal abundances in PHL 346 (on the scale log $[H] = 12.0$) are listed in Table 2, along with the normal Population I OB star values (He, Wolff and Heasley 1985; N, Dufton, Kane, and McKeith 1981; C, O, Kane, McKeith, and Dufton 1980; Mg, Lamers, van der Hucht, and Snijders 1973; Al, Sadakane, Takada, and Jugatu 1983; Si, Kamp 1982; P, S, Peters 1976; Fe, Kodaira and Scholz 1970). Since the Fe III λ4164.73 line has been found to give systematic underabundances with respect to those derived from other transitions (Hardorp and Scholz 1970), it was excluded from the abundance analysis. Error bars on the abundances refer to the sample standard deviation obtained whenever more than one equivalent width was analyzed. It should

TABLE 1

EQUIVALENT WIDTHS OF STELLAR ABSORPTION LINES IN PHL 346 SPECTRA

Species	W_λ	Species	W_λ
O II λ3911.96	102[a]	N II λ4227.75	47
O II λ3912.09	...	N II λ4236.93	66
C II λ3918.98	234	N II λ4237.05	...
N II λ3919.01	...	N II λ4241.78	125
O II λ3919.29	...	P III λ4246.68	52
C II λ3920.68	215	S III λ4253.59	166
He I λ3935.91	79	O II λ4253.74	...
O II λ3945.05	74	O II λ4253.98	...
O II λ3954.37	107	C II λ4267.02	331
He I λ3964.73	252	C II λ4267.27	...
O II λ3982.72	133	S III λ4284.99	90
S III λ3983.77	...	O II λ4303.82	60
N II λ3995.00	167	O II λ4317.14	95
He I λ4009.27	518	O II λ4319.63	79
He I λ4026.19	1316	O II λ4319.93	...
He I λ4026.36	...	O II λ4345.56	68
N II λ4035.09	76	O II λ4349.43	111
O II λ4035.09	...	S III λ4361.53	74
O II λ4041.31	86	O II λ4366.90	90
N II λ4041.32	...	N II λ4432.74	28
N II λ4043.54	73	He I λ4437.55	151
O II λ4060.58	85	O II λ4443.05	48
O II λ4060.98	...	N II λ4447.03	117
O II λ4069.64	192	O II λ4448.21	22
O II λ4069.90	...	O II λ4452.37	45
O II λ4072.16	122	He I λ4471.48	1059
C II λ4074.53	71	He I λ4471.69	...
C II λ4074.89	...	Al III λ4479.89	96
O II λ4075.87	260	Al III λ4479.97	...
C II λ4076.00	...	Mg II λ4481.13	227
O II λ4078.86	55	Mg II λ4481.33	...
O II λ4085.12	73	Al III λ4512.53	56
O II λ4087.16	54	Al III λ4528.91	132
Si IV λ4088.86	104	Al III λ4529.18	...
O II λ4089.29	...	N II λ4530.40	52
O II λ4092.50	59	Si III λ4552.65	280
Si IV λ4116.10	30	Si III λ4567.87	230
O II λ4119.22	492	Si III λ4574.78	151
O II λ4120.28	...	O II λ4590.97	79
O II λ4120.55	...	O II λ4596.17	80
He I λ4120.81	...	N II λ4601.48	146
He I λ4120.99	...	O II λ4602.11	...
O II λ4121.48	...	N II λ4607.15	113
Si II λ4128.05	94	O II λ4609.42	76
Fe III λ4164.73	57	N II λ4613.87	116
Fe III λ4166.84	61	N II λ4621.39	115
He I λ4168.97	145	N II λ4630.54	169
O II λ4169.23	...	O II λ4638.85	116
N II λ4176.16	55	O II λ4641.81	165
O II λ4185.46	56	N II λ4643.09	114
O II λ4189.79	59	C III λ4647.40	41
P III λ4222.14	50	O II λ4649.14	150

[a] Equivalent widths for which more than one wavelength are quoted have been calculated as blends. Equivalent widths in milliangstroms.

be noted that *random* errors in the mean abundances will be smaller.

It may be seen from an inspection of Table 2 that the helium and metal abundances in PHL 346 are in excellent agreement with those of normal B stars, differences being typically less than 0.2 dex. This indicates that the star is not a subluminous dwarf close to the plane, since these should have Population II chemical compositions and hence should be metal-weak (Tobin and Kaufmann 1984; de Boer 1985).

From the atmospheric parameters, the mass and lifetime of PHL 346 were derived using the evolutionary tracks of Maeder (1981) and were found to be $M = 13 \pm 2\ M_\odot$ and $T_{\rm evol} = 11 \times 10^6$ yr. A maximum value of $T_{\rm evol} = 17 \times 10^6$ yr was deduced by changing both the effective temperature and gravity by their estimated uncertainties. The values of $T_{\rm eff}$, log g, and mass imply an absolute bolometric magnitude of $M_{\rm bol} \approx -6.1$, and adopting the bolometric correction of BC ≈ -2.4 (Kurucz 1979) gives an absolute visual magnitude $M_v \approx -3.7$. Including a small extinction correction to allow for the observed reddening, $E(B-V) \approx 0.05$, then leads to a distance of $r = 10.2 \pm 1.7$ kpc, giving a z distance from the galactic plane of $z = 8.7 \pm 1.5$ kpc.

Because of the high galactic latitude of PHL 346 ($b \approx -58°$), its radial velocity (V_r) should give a good estimate of the velocity in the z direction, V_z (Keenan and Lennon 1984). A radial velocity of $V_r = +66 \pm 10$ km s^{-1} was determined from the wavelength shifts of stellar lines in the spectra, and, after correcting for the effects of galactic rotation (Keenan and Dufton 1983; Carney 1984), a value of $V_z = +56 \pm 10$ km s^{-1} was found. This velocity, coupled with the gravitational acceleration $g(z)$ from House and Kilkenny (1980), implies that the star would have taken $63 \pm 7 \times 10^6$ yr to reach its present position if it were ejected from the galactic plane, which is approximately a factor of 4 larger than the maximum lifetime of the star. Conversely, the present velocity would have to be $V_z \geq 500$ km s^{-1} for it to have reached its current z distance in less than the maximum lifetime, which is clearly incompatible with the observational data. We must therefore conclude that PHL 346 has been formed far from the galactic plane. Although it is difficult to envisage how this process could occur in view of the low gas density present in the galactic halo (Savage and de Boer 1981), one possible mechanism has been proposed by Dyson and Hartquist (1983). In their model, shock-induced star formation may take place during collisions between cloudlets within intermediate and high velocity clouds at high galactic latitudes, resulting in $\sim 10^3$ early-type stars being formed in the halo every 10^7–10^8 yr.

From the maximum lifetime of PHL 346, its velocity V_z, and the gravitational acceleration $g(z)$, it is possible to calculate the minimum z distance from the plane at which the star could have been formed, a value of ~ 6 kpc being inferred. Lockman and his coworkers (Lockman, Hobbs, and Shull 1986; Lockman 1984) point out that the H I layer in the galaxy does not extend much beyond $z \approx 1$ kpc. However Kaeble, de Boer, and Grewing (1985) and West *et al.* (1985) found high-velocity material that may exist up to 6 kpc from the disk, and which is probably returning to the plane in a "galactic fountain" type

TABLE 2

MEAN LOGARITHMIC HELIUM AND METAL ABUNDANCES IN PHL 346[a]

Element	Mean Abundance	Normal B-Star Value
He	10.99 ± 0.16	10.93
C	8.3 ± 0.2	8.2
N	8.0 ± 0.2	8.0
O	8.6 ± 0.2	8.8
Mg	7.5	7.4
Al	6.3 ± 0.2	6.3
Si	7.5 ± 0.2	7.5
P	5.6 ± 0.2	5.5
S	7.2 ± 0.1	7.2
Fe	7.6	7.5

[a] On the scale log [H] = 12.0.

flow (de Boer and Savage 1984; Bregman 1980). Therefore the most plausible explanation for the existence of PHL 346 at its present position is that it formed out of galactic fountain gas at a considerable distance ($z \approx 6$ kpc) from the disc.

We plan to extend this work by analyzing the spectra of other faint early-type high-latitude stars. Such studies should lead to estimates both of the fraction of halo stars formed *in situ*, and the range of z distances over which this occurs.

We would like to thank Professors A. E. Kingston, P. G. Burke FRS, and H. B. Gilbody for their continued interest in the work. We are grateful to the staff of the La Palma Observatory, and especially N. Reid for his assistance with the observations. F. P. K. acknowledges financial support from the SERC, and P. J. F. B. holds a postgraduate studentship from the Department of Education for Northern Ireland. Most of the calculations were carried out on the CRAY-1S computer at the University of London Computer Center using software implemented by A. E. Lynas-Gray on behalf of the SERC Collaborative Computational Project 7.

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